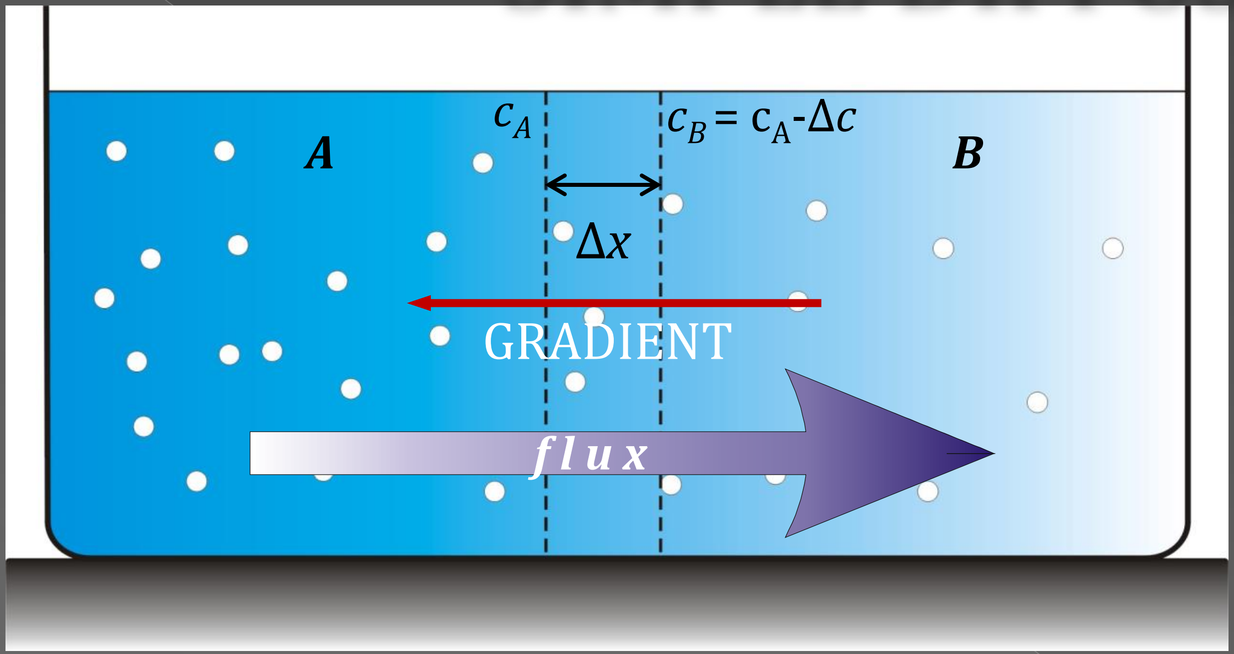
TRANSPORT OF SOLUTES AND WATER THROUGH MEMBRANES AND CAPILLARY WALLS

- DIFFUSION
- OSMOSIS
- FILTRATION

By Marek Tuliszka D.Sc.
Department of Biophysics
Poznan University of Medical Sciences

SIMPLE DIFFUSION



Fick's law:

$$\frac{\Delta \boldsymbol{n}}{\Delta \boldsymbol{t} \cdot \boldsymbol{S}} = -D\,\frac{\Delta c}{\Delta x}$$

$$P = \frac{D}{\Delta x}$$

$$\frac{\Delta n}{\Delta t \cdot S} = P(c_B - c_A)$$

Each transport process requires a proper stimulus which is a driving „force" for the process to occur:

GRADIENT $\longrightarrow \dfrac{\Delta c}{\Delta x}$

The amount of substance $\boldsymbol{\Delta n}$ (in moles or grams) crossing the surface area $\boldsymbol{S}$ in unit time $\boldsymbol{\Delta t}$ (***flux***) is proportional to the concentration gradient (!). The coefficient of proportionality, $\boldsymbol{D}$ is called the coefficient of the diffusion.

The coefficient of diffusion

For spherical molecules that are much larger than the surrounding solvent molecules the following relation has been obtained:

$$D = \frac{kT}{6\pi r\eta}$$

← The Stokes-Einstein relation

k - Boltzman's constant
T - absolute temperature
r - radius of diffusing molecule
η - viscosity of solvent

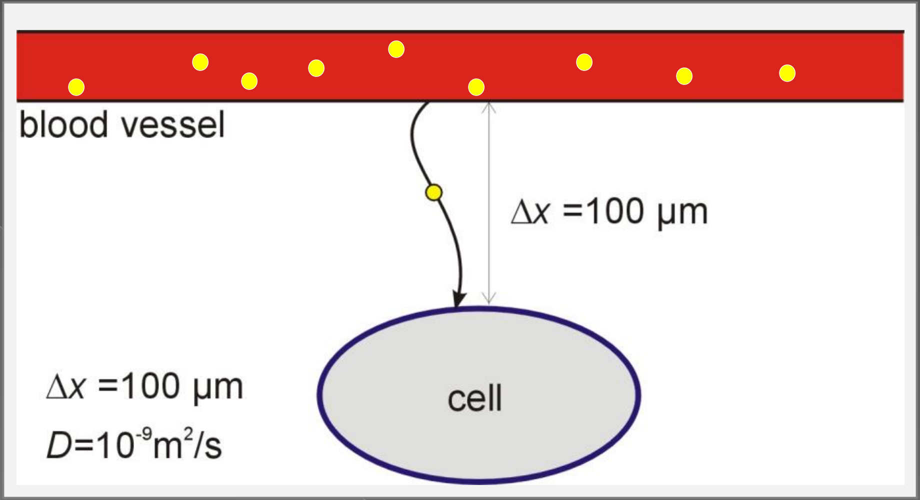
The Einstein-Smoluchowski equation

$$\overline{(\Delta x)^2} = 2Dt$$

where:

Δx stands for the average displacement squared,

t is the time elapsed since the molecules started diffusing.



$$t = \frac{\overline{(\Delta x)}^2}{2D}$$

for Δx = 0.1 mm:

→ 5s

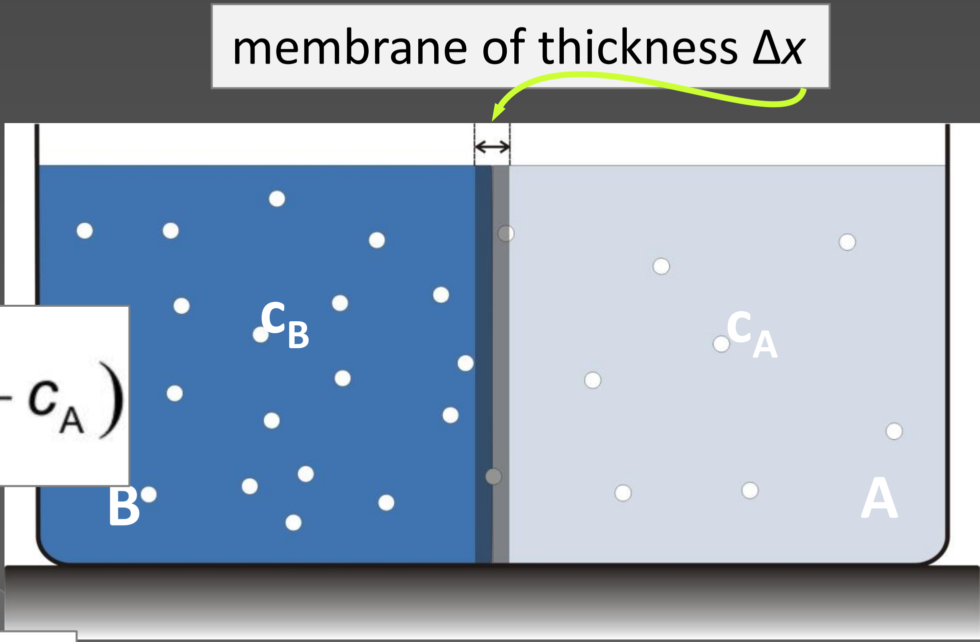
for Δx = 1mm:

$$t = \frac{10^{-6}\,m^2}{2\times10^{-9}\,m^2/s} = 500\ s$$

Permeability

$$\frac{\Delta n}{\Delta t} = -DS\frac{\Delta c}{\Delta x}$$

(Fick's law)



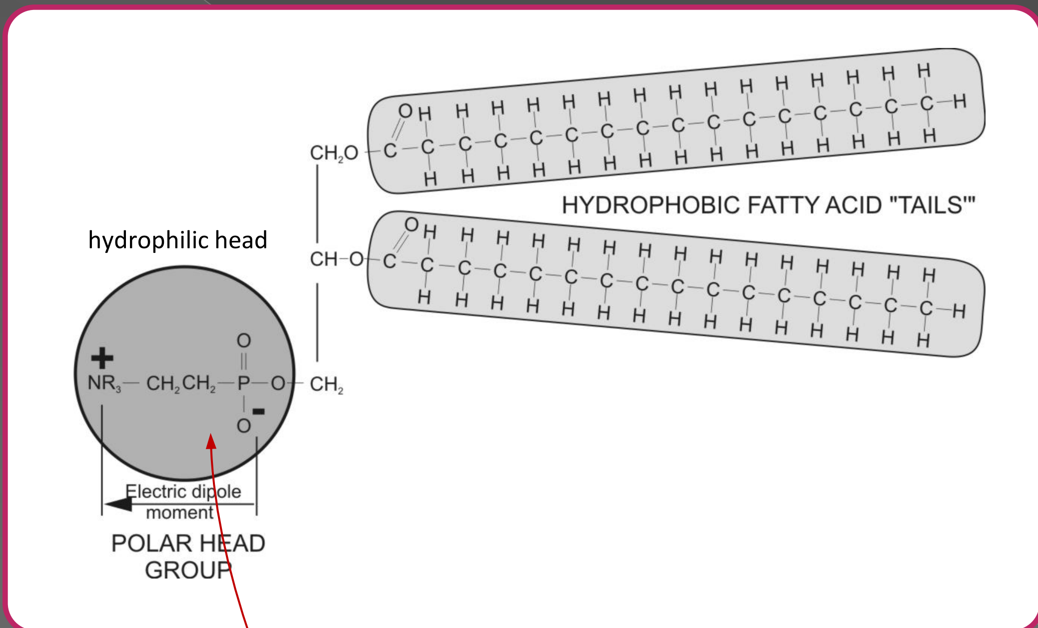
$$\frac{\Delta n}{\Delta t} = -SD\frac{c_A - c_B}{\Delta x} = S\frac{D}{\Delta x}(c_B - c_A)$$

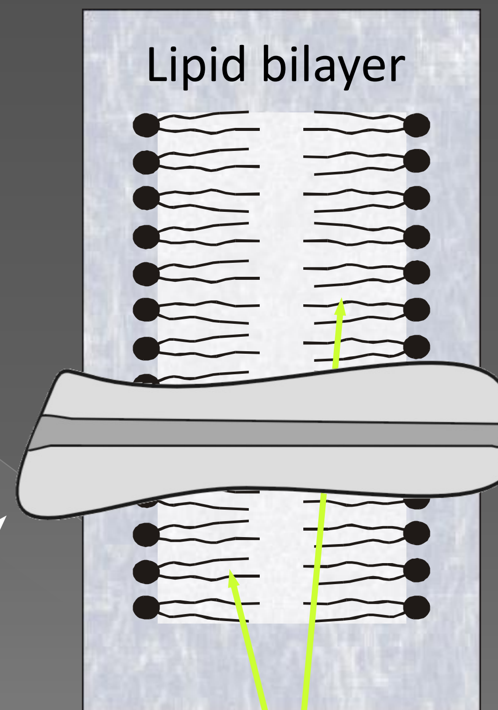
$$\frac{\Delta n}{\Delta t} = SP(c_B - c_A)$$

DIFFUSIONAL FLUX OF A SUBSTANCE ACROSS A MEMBRANE MAY BE ALTERED BY CHANGES IN ONE OF THE VARIABLES:

- membrane surface area S
- concentration gradient
- membrane permeability *P*

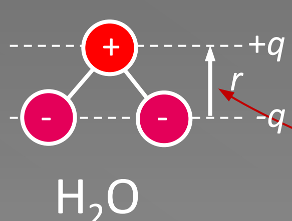
The membrane structure





integral protein: the channel

hydrophobic interior



electric dipole moment

p=q·r

FACTORS AFFECTING MEMBRANE PERMEABILITY

- THE MEMBRANE PERMEABILITY CAN BE CHANGED AS A RESULT OF OPENING AND CLOSING OF ION CHANNELS !!!.

THE PROTEINS THAT FORM ION CHANNELS CAN UNDERGO CONFORMATIONAL CHANGES THAT RESULT IN OPENING AND CLOSING OF CHANNELS.

TWO GENERAL EVENTS ARE KNOWN TO CHANGE THE CONFORMATION OF THE ION-CHANNEL PROTEINS:

- Binding of chemicals to the channel proteins
- Changes in membrane potential which acts upon the charged regions of the channel proteins to produce change in their shape.

Transport categories

Passive transport
- in accordance with naturally existing stimuli

simple diffusion

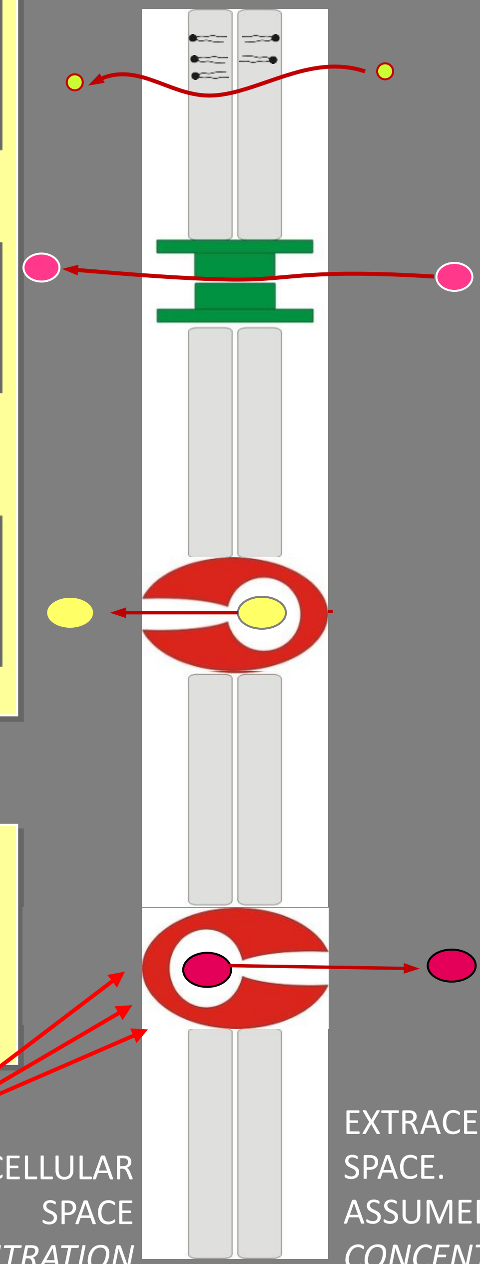
channel mediated diffusin

carrier mediated diffusin

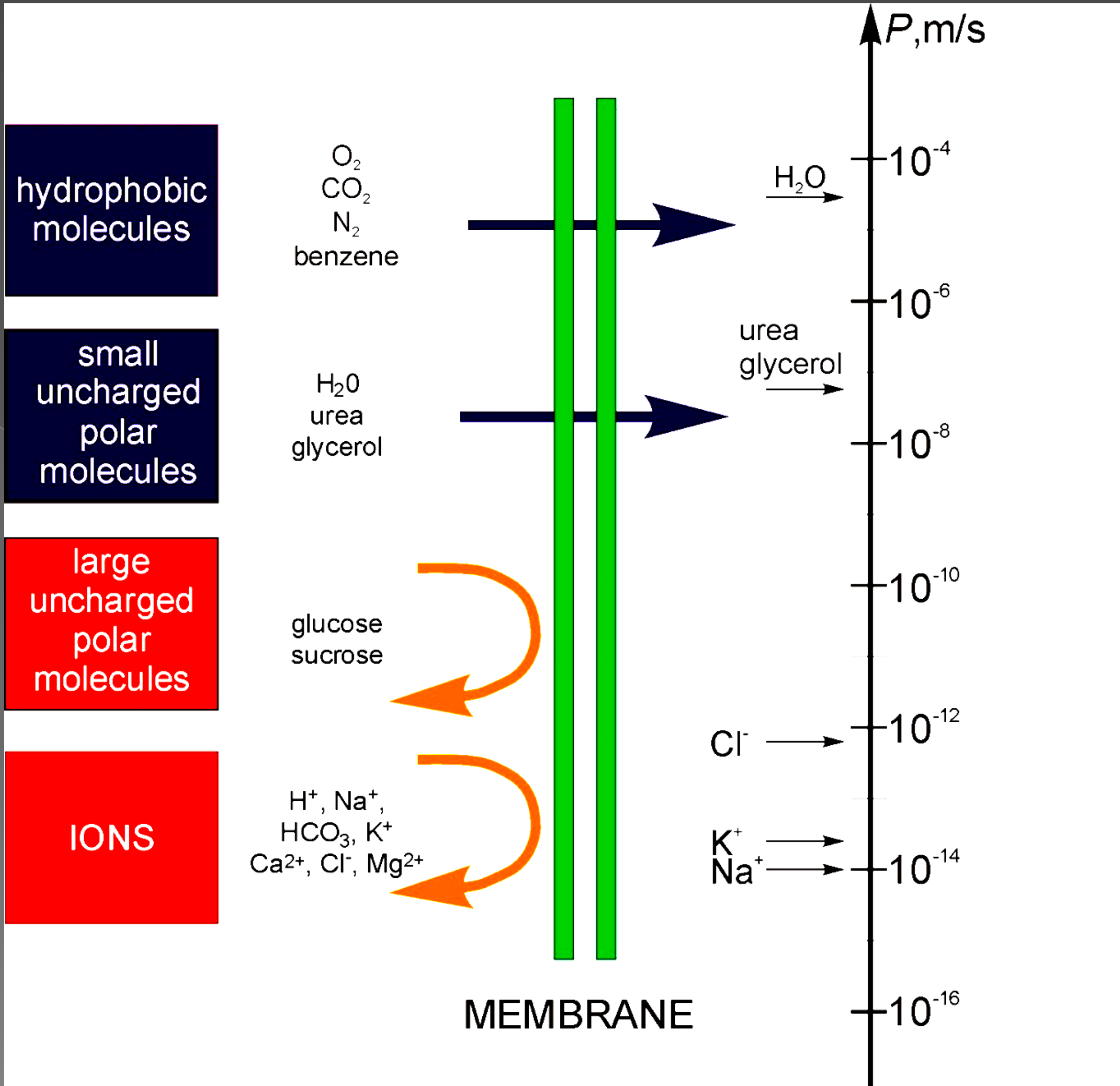
Active transport
- against stimuli

Carrier mediated transport

Dissociation of ATP → energy



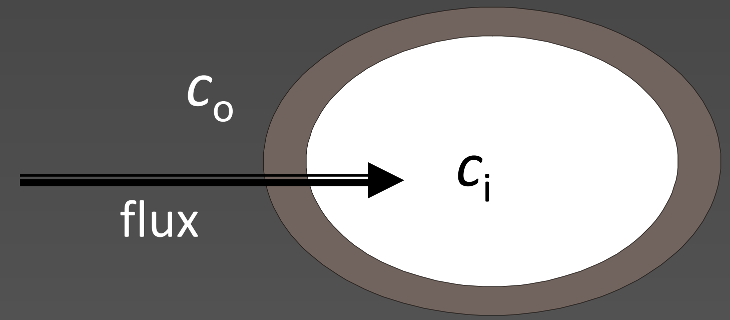
Permeability: comparison



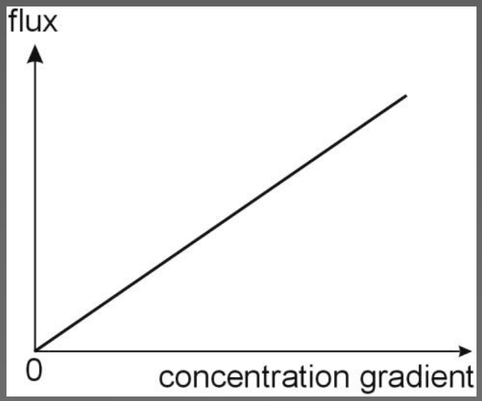
Permeability coefficients *P* (m/s) for the passage of various molecules through synthetic lipid bilayer

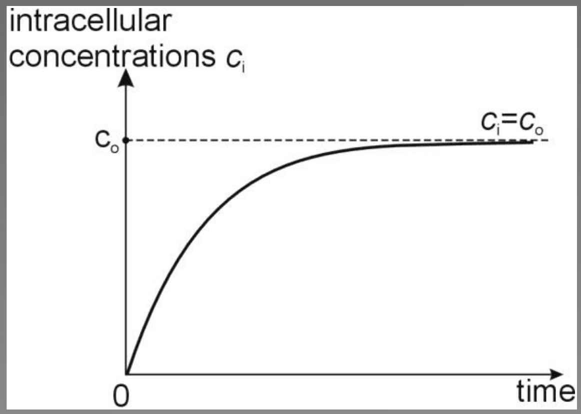
Summary

$c_o > c_i$



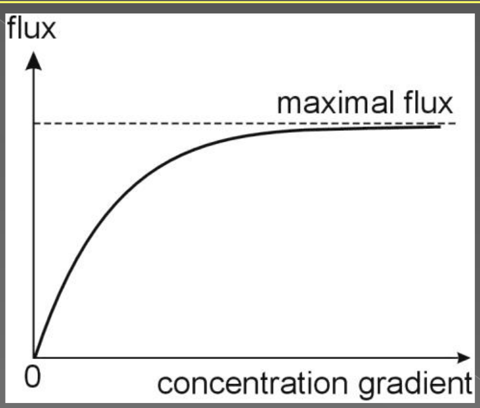
simple diffusion

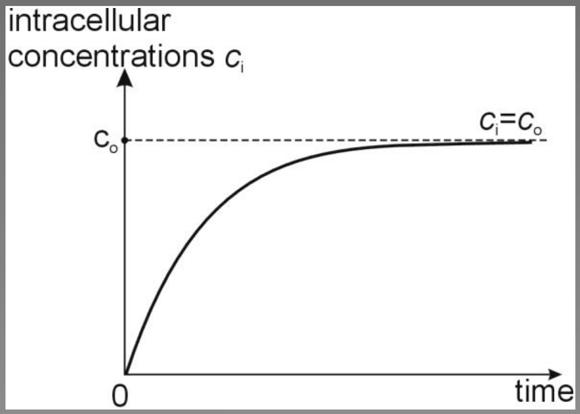




facilitated diffusion

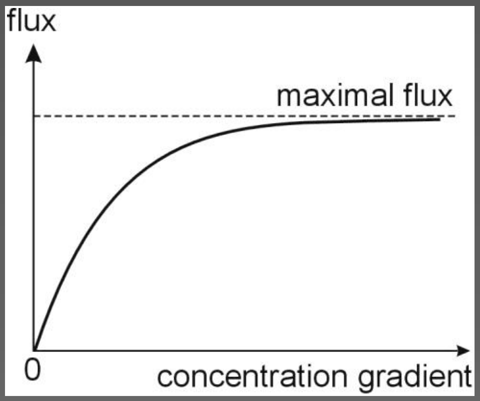
(channel and carrier mediated)

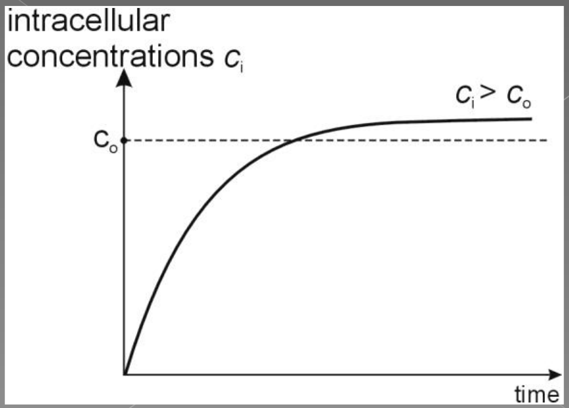




active transport

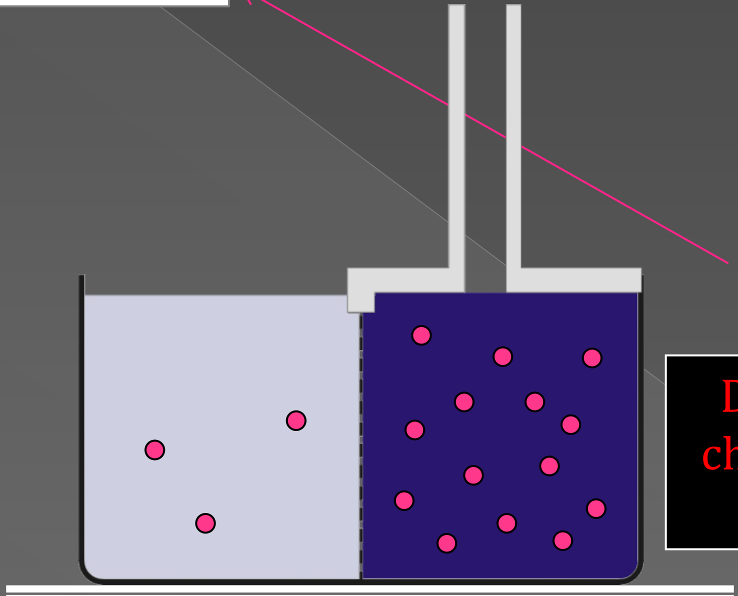
(carrier mediated)





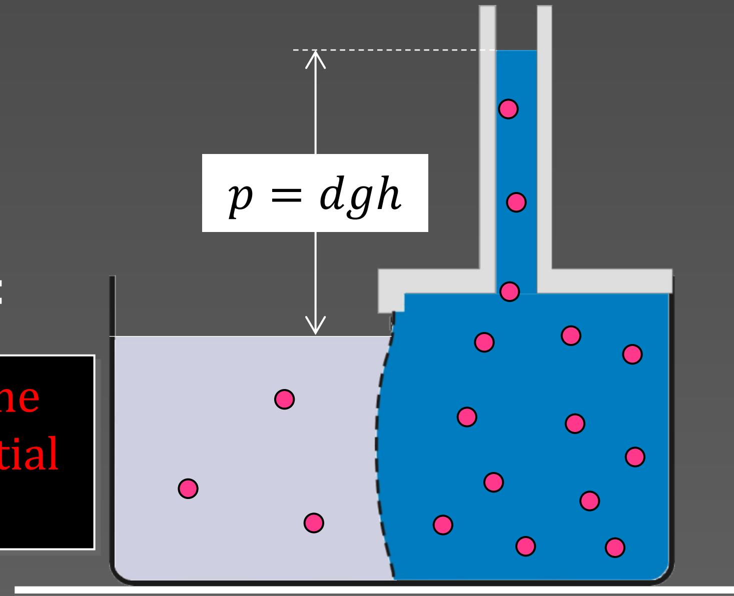
OSMOSIS

$\mu_i = \mu_i^0 + RT \cdot \ln x_i$



STIMULUS:

Difference in the chemical potential of water!



Semi-permeable membrane
(impermeable for solute molecules!)

d - density

The van't Hoff equation

$$\pi = iRTc_m$$

- π - osmotic pressure
- R - ideal gas constant,
- i - number of ions formed by dissociation of a solute molecule
- T - absolute temperature,
- c_m - molar concentration of solute (in mole per liter).

OSMOTIC PRESSURE

$\pi = iRTc_m$

for KCl, NaCl, $MgSo_4$ $i = 2$, for glucose $i = 1$

$\pi = \varphi iRTc_m$

φ - correction factor called the ***osmotic coefficient***

$\pi = (\varphi ic_m)RT$

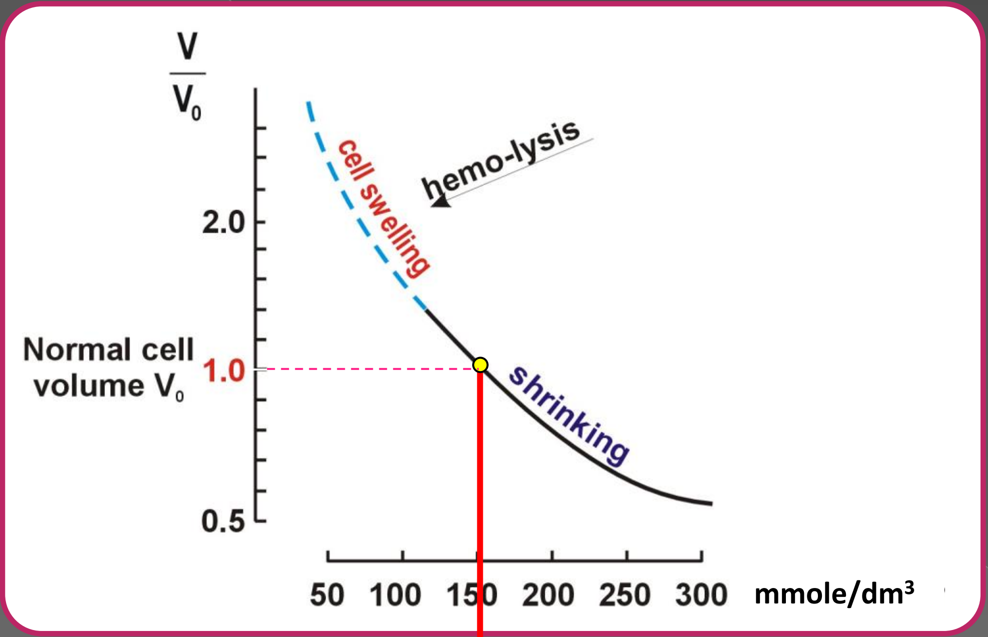
φic_m - osmolar concentration or osmolarity

$\varphi_{NaCl} = 0.93$
$\varphi_{KCl} = 0.92$
$\varphi_{MgSO_4} = 0.58$
$\varphi_{glucose} = 1.01$

Example: What is the osmolarity of a 0.154 mole/dm³ NaCl solution (the value typical for red blood cells at 37°C) :

$$osmolarity_{NaCl} = 0.93 \times 2 \times 0.154 \frac{\text{mole}}{\text{dm}^3} = 0.29 \frac{\text{osmole}}{\text{dm}^3}$$

OSMOTIC BEHAVIOUR OF RED BLOOD CELLS



The osmotic behaviour of human red blood cells in NaCl solutions.
At 0.154 mole (**isotonic solution**) the red cell has its normal volume.

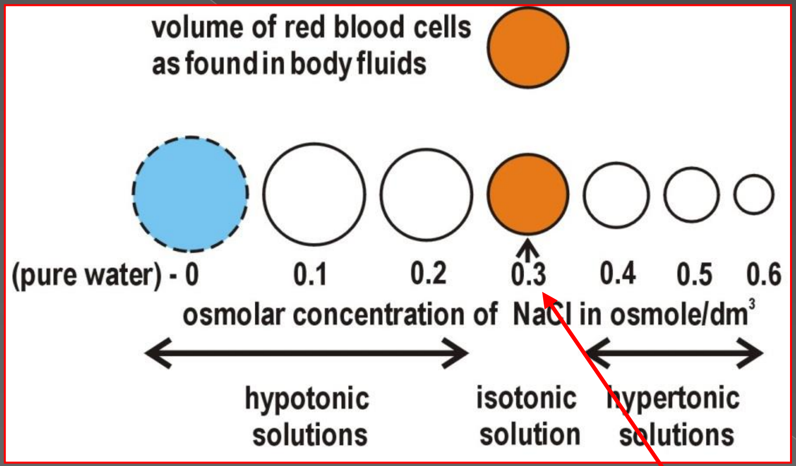
0.29 osmole/dm^3
isotonic solution
(0.154 mole/dm^3 NaCl solution)

It shrinks in more concentrated (**hyper-tonic**) solutions.

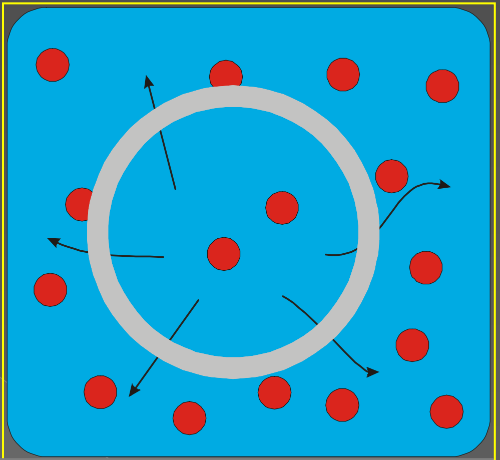
It swells in more dilute (**hypo-tonic**) solutions.

Tonicity is the ability of the particles in solution to cause changes in a cell volume

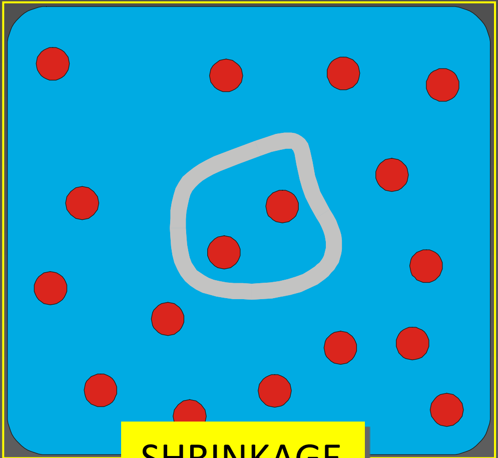
OSMOTIC BEHAVIOUR OF RED BLOOD CELLS



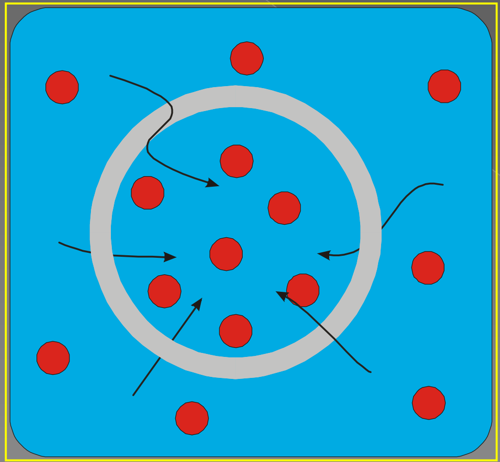
Comparison of the volumes of red blood cells in solutions of different concentration of NaCl with the volume of red blood cell surrounded by a body fluids.



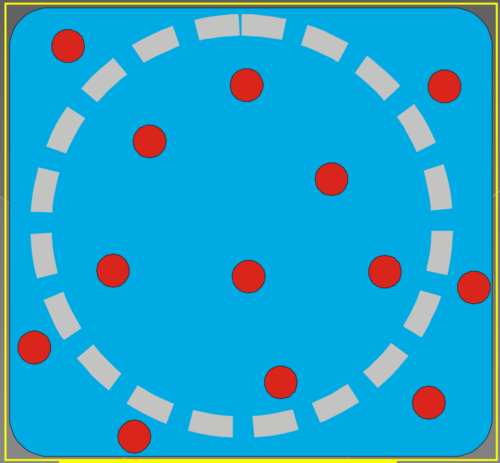
HYPERTONIC SOLUTION



SHRINKAGE



HYPOTONIC SOLUTION



SWELLING
(HEMOLYSIS POSSIBLE)

OSMOTIC FLOW OF SOLVENT

$$\frac{\Delta V}{S\Delta t} = L_V \Delta\pi$$

ΔV is the volume of solvent flowing through membrane area of surface ***S*** in unit time Δ***t***,

L_V is called the hydraulic conductivity,

$\Delta\pi$ stands for the difference in osmotic pressure.

$$\frac{\Delta V}{S\Delta t} = \sigma L_V \Delta\pi$$

σ – the reflection coefficient

σ is a property of a particular solute (!) and a particular membrane (!) and may represent the osmotic flow induced by the solute as a fraction of the theoretical maximal osmotic flow.

$$\sigma = \left(1 - \frac{P_{solute}}{P_{solvent}}\right)$$

σ for porous dialysis membranes:

urea	- 0.024
glucose	- 0.205
sucrose	- 0.368
insulin	- 0.760

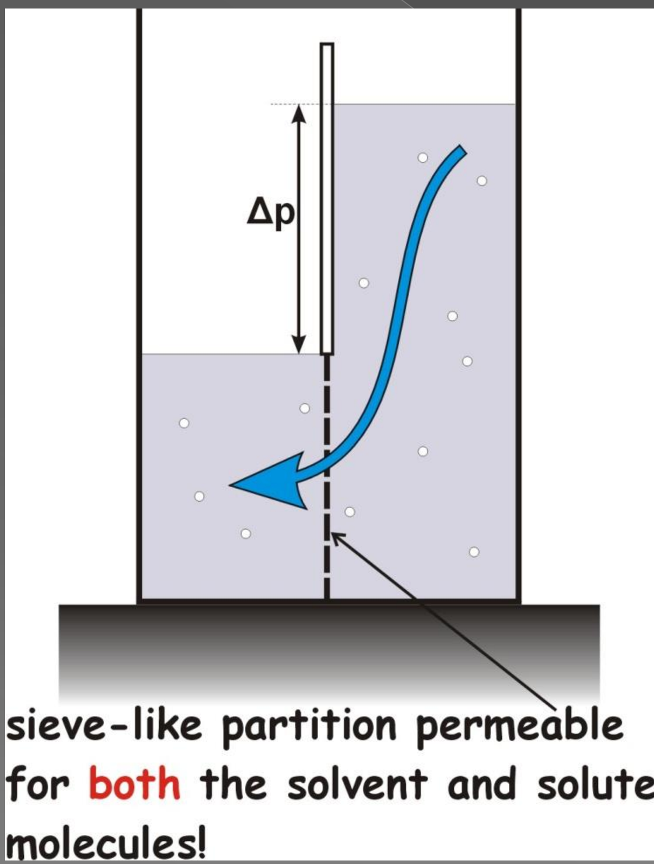
NO OSMOTIC FLOW

- If $P_{solute} = P_{solvent}$ $\sigma = (1 - 1) = 0$ no reflection!
- If $P_{solute} = 0$ $\sigma = (1 - 0) = 1$ semi-permeable membrane

„PURE" OSMOTIC FLOW

FILTRATION

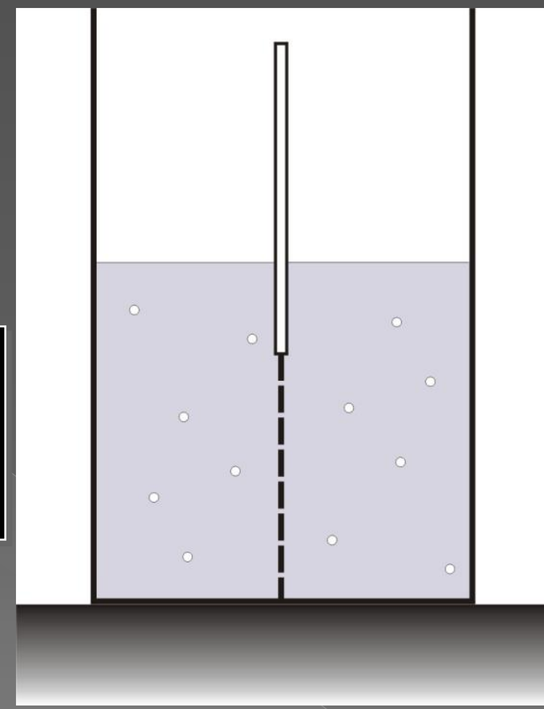
INITALLY



STIMULUS:

DIFFERENCE IN FLUID PRESSURE: Δp !

FINALLY

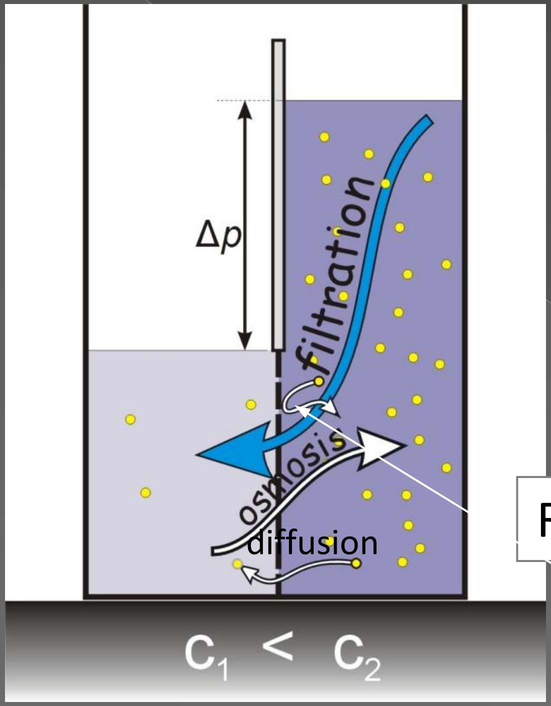


$\Delta p = 0$
no flow

$$\frac{\Delta V}{S\Delta t} = L_V \Delta p$$

L_v - hydraulic conductivity
Δp - difference in pressure

THE NET FLOW OF SOLVENT



REFLECTION

$0 < \sigma < 1$

THE OSMOTIC FLOW

$$\frac{\Delta V}{S\Delta t} = \sigma L_V \Delta\pi$$

$$J_V^{osmosis} = \sigma L_V \Delta\pi$$

FILTRATION

$$\frac{\Delta V}{S\Delta t} = L_V \Delta p$$

$$J_V^{filtration} = L_V \Delta p$$

$$J_V^{water} = J_V^{filtration} - J_V^{osmosis}$$

$$J_V^{water} = L_V (\Delta p - \sigma\Delta\pi)$$

1. $\sigma = 0$ there is no osmotic flow; equalisation of concentration occurs by the diffusion and by solvent drag

$$J_V^{water} = L_V \Delta p$$

2. $\sigma = 1$ the reflection occurs; equalisation of concentration occurs by the osmotic flow and filtration

$$J_V^{water} = L_V (\Delta p - \Delta\pi)$$

THE STARLING HYPOTHESIS

the relationship between the static fluid pressure and oncotic (*osmotic pressure due to molecules of proteins*) pressure and the role of these agents in regulating fluid passage across a capillary endothelium.

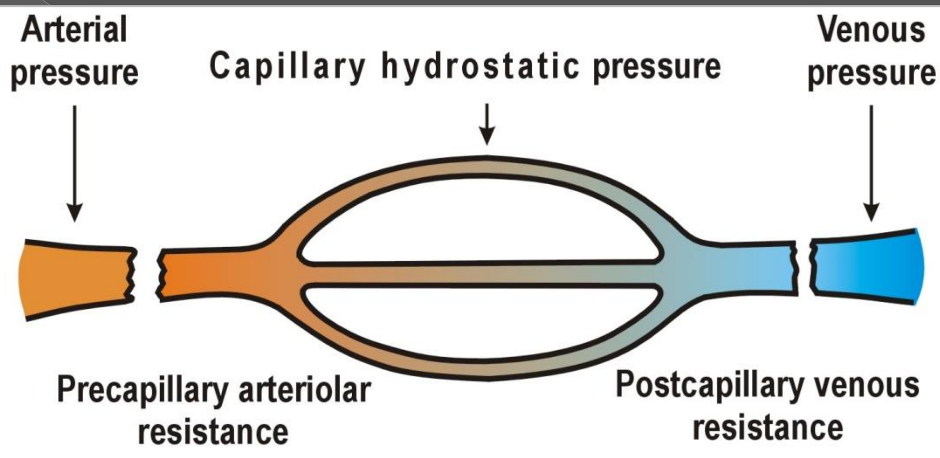


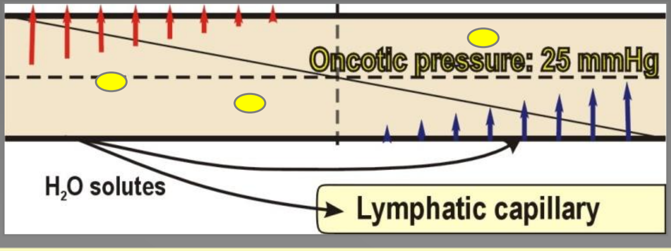
Diagram of the vascular bed, illustrating precapillary and postcapillary pressures and resistances used in the calculation of capillary hydrostatic pressure.

$\sigma = 1$

$$J_V^{water} = L_V(\Delta p - \Delta\pi)$$

FILTRATION ABSORPTION

Capillary pressure: 32 mmHg



Venous pressure: 15 mmHg

Interstitial fluid pressure (assume -1)
Interstitial fluid oncotic pressure (assume 0)

32-(-1)=33 - outside
25-0=25 - inside
8 net outside - **filtration**

15-(-1)=16 - outside
25-0=25 - inside
9 net inside - **absorption**

Bowman's capsule

AFFERENT END

out
p_{GC} = 45 mm Hg
π_{BS} = 0 mm Hg

in
p_{BS} = 10 mm Hg
π_{GC} = 25 mm Hg

----

p_{NET} = 10 mm Hg

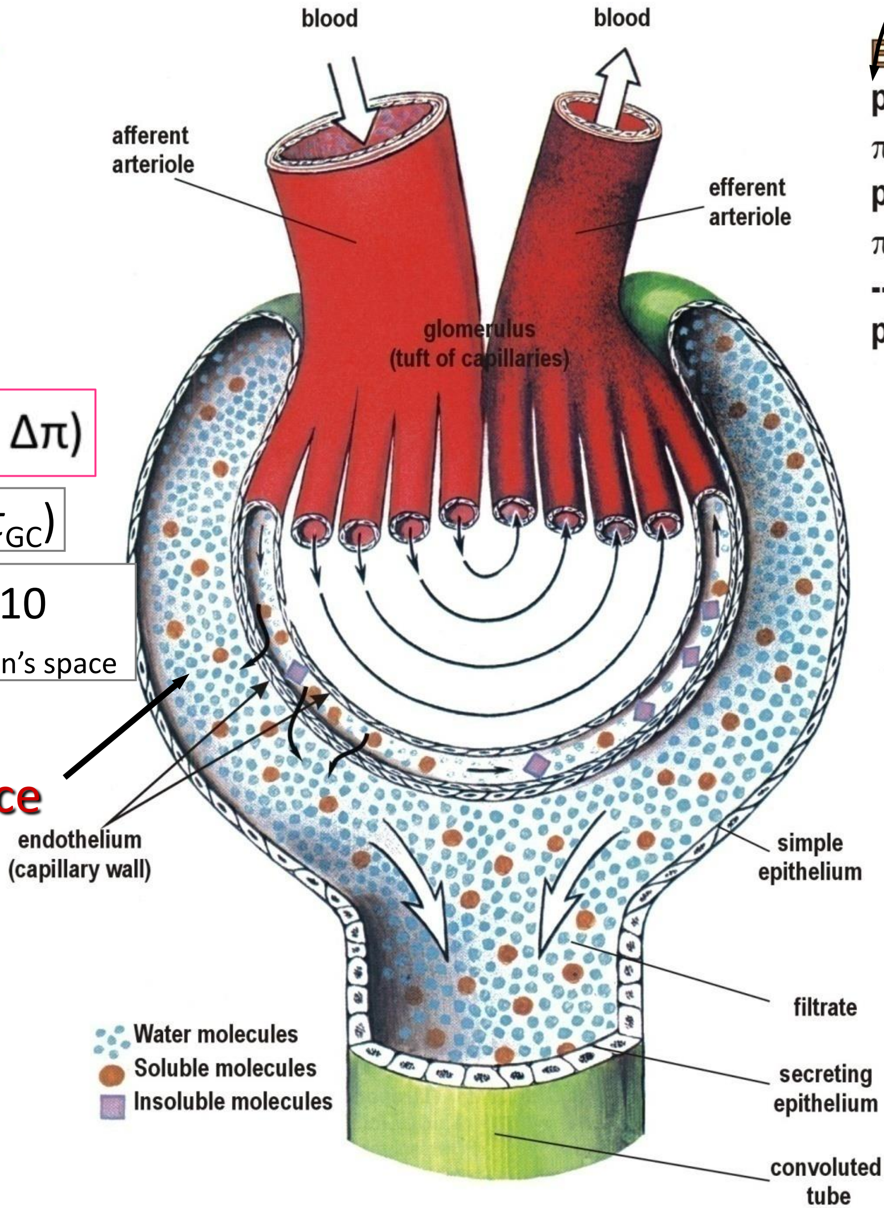
$$J_V^{water} = L_V(\Delta p - \Delta\pi)$$

$(p_{GC}+\pi_{BS})$ -$(p_{BS}+\pi_{GC})$

(45+0)-(10+25)=10

filtration toward Bowman's space

Bowmans' space



glomerular capillary fluid pressure

EFFERENT END

p_{GC} = 44 mm Hg
π_{BS} = 0 mm Hg
p_{BS} = 10 mm Hg
π_{GC} = 34 mm Hg

----

p_{NET} = 0 mm Hg

Bowman's space oncotic pressure

Bowman's space fluid pressure

glomerular capillary oncotic pressure

$$J_V^{water} = L_V(\Delta p - \Delta\pi)$$

$(p_{GC}+\pi_{BS})$ -$(p_{BS}+\pi_{GC})$

(44+0)-(10+34)=0

DIALYSIS

- a method used to remove urea from blood when the kidneys do not function.

- Urea is in the interstitial brain fluid and in the cerebrospinal fluid in the same concentration as in the blood plasma.

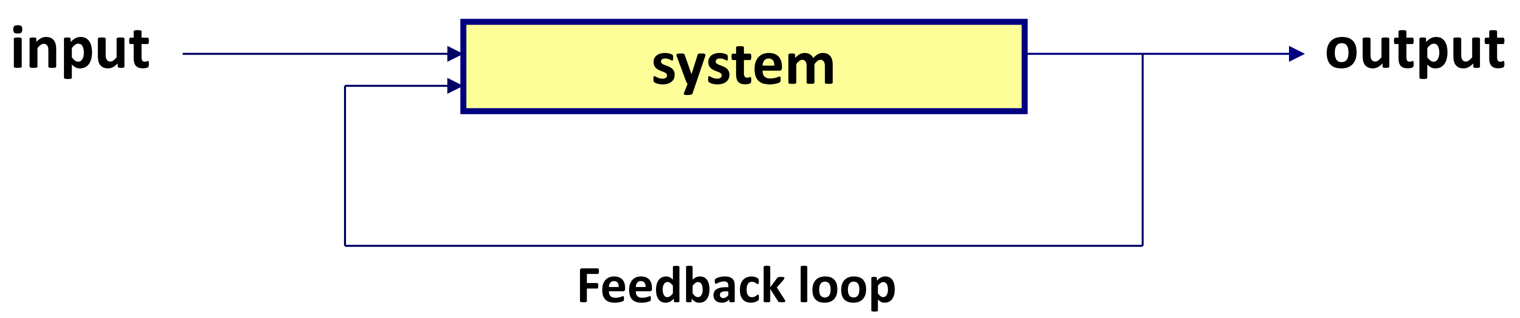
- Permeability of the brain capillary membrane („barrier”) is low, so equilibration takes several hours. Water, oxygen and nutrients cross from the capillary to the brain at a much faster rate than urea.

- As the blood plasma urea concentration drops, as a result of developing dialysis, there appears temporary osmotic pressure difference. It results from the excess of urea in the interstitial and cerebrospinal fluid - osmotic pressure of urea molecules drives water into the brain interstitial space.

Cerebral oedema may appea causing severe headache !

Feedback

A characteristic of a control system in which the output response influences the input to the control system.

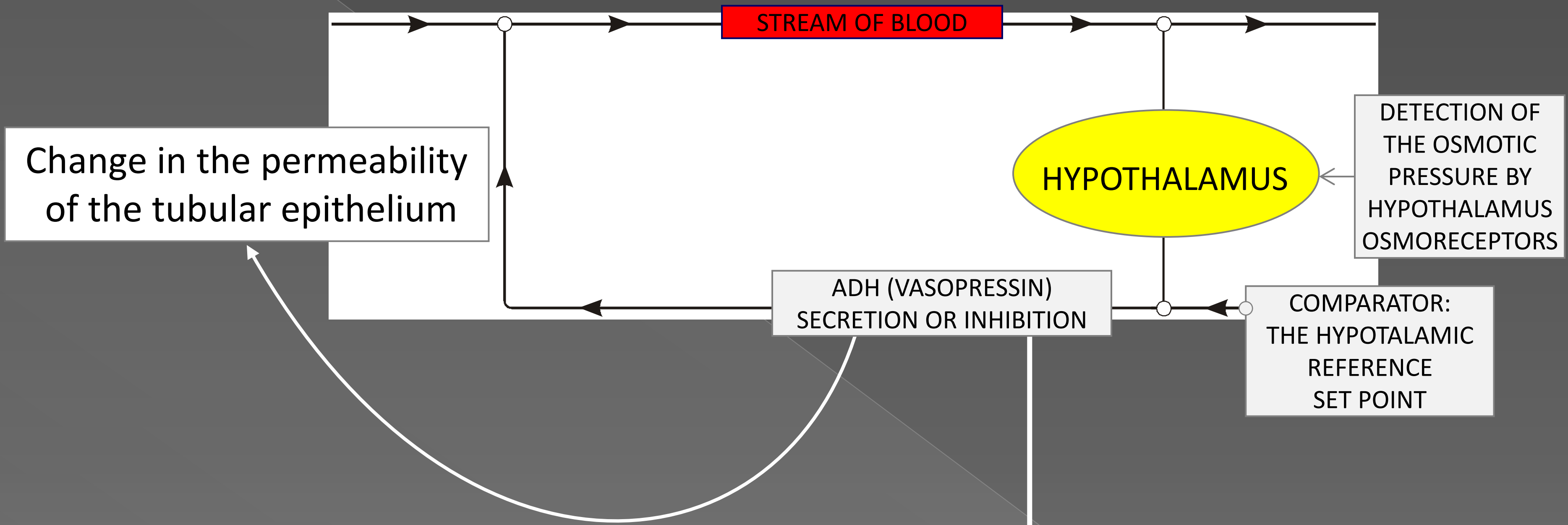


Negative feedback:

is a type of feedback during which a system responds so as to reverse the direction of change.

Since this process tends to keep things constant, **it is stabilizing** and attempts to maintain **homeostasis**.

NEGATIVE FEEDBACK LOOP FOR CONTROL OF BODY FLUIDS



Cells located in the hypothalamus but distinct from those that synthesise ADH (anti diuretic hormone, *vasopresin*) are involved in sensing in body fluid osmolarity.

These cells termed ***osmoreceptors*** appear to behave as osmometers and sense changes in body fluid osmolarity by either shrinking or swelling.

Several reasons can give rise to localized swelling called *oedema,* that is a collection of fluids in tissues or body organs.

EXAMPLES:

Oedema in the heart failure

THE RIGHT HEART FAILURE

- results in abnormal collection of interstitial fluid in the lower parts of the body.

Mechanism: The right heart pumps blood from the veins through the lungs. If the heart can no longer handle this load, the venous blood is not removed rapidly enough, and the pressure in veins (static fluid pressure) and at the venous end of capillary bed **rises**.

More fluid flows from capillaries to the interstitial space. The interstitial pressure raises until the net flow is again equal to zero. **The observed result is the edema.**

THE LEFT HEART FAILURE

Mechanism: if the left hart fails to pump the blood from the lungs, the blood will accumulate in the blood vessels of the lung, leading to a pressure build-up in the lung capillaries and to filtration of fluids into the lung space.

The observed result is pulmonary edema

In liver diseases:

Diseases of the liver can block the return of venous blood from the intestine to the heart leading to abdominal oedema.

In kidney diseases (hypo-proteinemia)

If proteins are lost with the urine, the osmotic (oncotic) pressure decreases, diminishing the absorption at the venous end of the capillary bed.

In malnutrition (hypo-proteinemia)

- abdominal oedema

Oedema associated with an injury

Mechanism:

An increased permeability of destroyed or damaged capillary walls to large molecules locally reduces the osmotic pressure. This makes filtration dominating over absorption.